"The Electrical Conductivity imparted to a Vacuum by Hot Conductors." By O. W. RICHARDSON, B.A., B.Sc., Fellow of Trinity College, Cambridge. Communicated by Professor J. J. THOMSON, F.R.S. Received February 28,—Read March 26, 1903.

(Abstract.)

The experimental part of this paper is an investigation of the electrical conductivity of the space surrounding hot surfaces of platinum, carbon, and sodium, at low pressures. In addition, the first portion of the paper is occupied in deducing a theory by which the experimental results are explained. Some of the results that have been obtained with platinum were described in a preliminary note read before the Cambridge Philosophical Society on November 25, 1901.

The present paper is subdivided as follows:—

A. Theoretical investigation.
   1. Calculation of the saturation current.
   2. Equilibrium of corpuscles near a hot conducting plane of infinite area.

B. Experimental investigation.
   1. Experiments with platinum.
   2. Experiments with carbon.
   3. Experiments with sodium.

C. Conclusion.

The experiments show that the negative leak from hot wires at low pressures is a definite function of the temperature of the wire, and increases very rapidly as the temperature is raised. Professor McClelland* had previously found that this leak was independent of the pressure at pressures less than 0·04 mm., whilst Professor J. J. Thomson† had shown in addition that the current was carried by corpuscles or electrons.

The theory here put forward to explain these facts, and those to be described later, is based on the corpuscular theory of conduction in metals. On that view a metal contains a very great number of free corpuscles whose mean free path is comparable with that of a molecule in air at atmospheric pressure. The corpuscles must, therefore, be moving with a distribution of velocity given by the Boltzmann-Maxwell law. Since the corpuscles do not escape from the metal at ordinary temperatures, it is evident that there must be a discontinuity of potential at the surface which prevents their escape.

* 'Camb. Phil. Soc. Proc.,' vol. 10, p. 241, and vol. 11, p. 296.
† 'Phil. Mag.,' vol. 48, p. 547.

On raising the temperature of the metal, the energy of the corpuscles is increased, and at high enough temperatures some of them will be able to shoot through the surface into the surrounding space.

The number of corpuscles which escape at any temperature has been calculated on this view. The saturation current, which corresponds to the number emitted per second, is given by the equation

$$C = n\epsilon S\left(\frac{R\theta}{2m\pi}\right)^{\frac{1}{2}} e^{-\Phi/R\theta},$$

where

n is the number of free corpuscles in 1 c.c. of the metal,
ϵ the charge on an ion,
S the area of the hot-metal surface,
R the gas constant for a single corpuscle, whose mass is m,
θ the absolute temperature, and
Φ the work done by an ion in passing through the surface layer.

The rate at which energy is emitted, due to this cause, is also calculated.

Owing to the important part which the ionisation from hot bodies has played in certain recent cosmological theories, the equations which determine the equilibrium of corpuscles near a plane surface of hot metal of infinite extent are also given and solved.

The chief problem which has been attacked experimentally is the way in which the saturation current from a negatively-charged hot metal surface to a neighbouring electrode varies with the temperature of the metal.

In the case of platinum, the hot metal consisted of a fine wire spiral passing along the axis of a surrounding cylindrical electrode. The temperature was obtained from the resistance of the wire.

In the case of carbon, the leak was measured from a small lamp filament to a surrounding cylinder. The temperature was estimated in two ways: (1) by fastening a platinum and platino-iridium thermocouple of very fine wire round the filament, and (2) from the resistance of the filament.

With sodium this method could not be adopted. The metal was distributed on the inner surface of a steel cylinder, and the current from it to an insulated wire inside the cylinder was measured. The temperature was obtained by a thermo-couple of copper and nickel. Owing, doubtless, to the peculiar shape of the electrodes and the somewhat high pressure of the gas, the current with sodium was never saturated. For this reason the current under a given voltage was measured instead of the saturation current.

Incidentally, it was found necessary to examine the relation between the current and the applied electromotive force. Current E.M.F. curves are given for all three substances, and, in the case of carbon,

for a considerable range of pressures. To account for the results at the higher pressures, it is necessary to assume that ions are produced by collisions.

The variation of current with temperature is examined over the following range:—

For platinum	from	10^{-10}	to	10^{-3}	ampère per sq. cm. of surface.
For carbon	,,	10^{-8}	,,	2	,, ,, ,,
For sodium	,,	10^{-11}	,,	2×10^{-2}	ampère total current.

The corresponding ranges of temperature for platinum and sodium are roughly from 1000° C. to 1600° C., and from 100° C. to 450° C. respectively. The small currents from sodium were measured with a quadrant electrometer, but as a general rule, a sensitive D'Arsonval galvanometer with suitable shunts was used.

Perhaps the most striking result of the investigation is the relatively enormous currents which have been obtained. The biggest leak measured was 0·4 ampère from a carbon filament to an electrode placed near it; this corresponded to a current of 2 ampères per sq. cm. of the carbon surface, the potential on the filament being -60 volts. The pressure in this experiment was only $\frac{1}{600}$th mm. This current and some of the largest currents from sodium were registered on a Weston ammeter.

In all these experiments the potentials employed were too small to maintain a discharge between the electrodes.

Throughout the range given above, the relation between the saturation current and the temperature was found to be represented by a formula of the type

$$C = A\theta^{\frac{1}{2}}e^{-b/\theta},$$

where A and b are constants for each conductor.

The values which have been found for these constants are—

$$\begin{array}{lll} \text{For platinum,} & A = 10^{26}, & b = 4 \cdot 93 \times 10^4. \\ \text{For carbon,} & A = 10^{34}, & b = \left.\begin{array}{r} 7 \cdot 8 \times 10^4. \\ 9 \cdot 7 \times 10^4. \\ 11 \cdot 9 \times 10^4. \end{array}\right\} \\ \text{For sodium,} & A = 10^{31}, & b = 3 \cdot 16 \times 10^4. \end{array}$$

The value of A varies very rapidly with the value found for b, so that only its order of magnitude is given.

The number n of free corpuscles in a c.c. of the metal is calculated from A. For platinum this gives $n = 10^{21}$, whereas Professor Patterson* found 10^{22}. In the case of the other conductors, the number found is absurdly great compared with Patterson's values.

* 'Phil. Mag.' [6], vol. 3, p. 655.

The discrepancy can be made to disappear by assuming a small temperature variation of b. This assumption is shown to be consistent with the general nature of b.

The work required to drive an ion through the surface layer is calculated, in each case, from the value of b, to which it is proportional. Dividing by the charge on an ion this yields the discontinuity of potential at the surface of the conductor. The values found for this are: for sodium, $\delta\phi = 2{\cdot}45$ volts, for platinum $\delta\phi = 4{\cdot}1$ volts, and for carbon $\delta\phi = 6{\cdot}1$ volts. These numbers are inversely proportional to the cube roots of the respective atomic volumes. This leads to the conclusion that the work required to force a corpuscle out of a metal varies, approximately at any rate, inversely as the cube root of the atomic volume of the metal.

In all these experiments, the current when the hot wire is charged positively is small compared with that obtained with the metal negatively charged. Only in the case of sodium was the positive current large enough to deflect a sensitive galvanometer.

The results which have been obtained are shown to furnish a complete explanation of the phenomenon known as the Edison effect.

The fact that such enormous currents are obtained at such very low pressures confirms the conclusion that the ions are not produced from the gas by its interaction with the metal. Calculation shows that to obtain the currents registered with carbon, each gas molecule would have to give rise to 25 ions each time it collided with the hot metal surface.

The energy lost owing to the escape of the corpuscles is compared with the energy emitted in the form of ordinary electromagnetic radiation. The former is shown to be smaller than the latter at the temperatures at which measurements have been made, but it increases more rapidly with the temperature.